AEDC-TR-76-126

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VARIABLE-AREA SUBSONIC DIFFUSER STUDY

ENGINE TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

September 1976

Final Report for Period July 1, 1975 – June 30, 1976

Prepared for

DIRECTORATE OF TECHNOLOGY (DY)
ARNOLD ENGINEERING DEVELOPMENT CENTER
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NOTICES

APPROVAL STATEMENT

This technical report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER AEDC-TR-76-126	2 GOVT ACCESSION NO.	3 RECIPIENT'S CATALOG NUMBER
4 TITLE (and Subtitle) VARIABLE-AREA SUBSONIC DIFFUSER STUDY		5 TYPE OF REPORT & PERIOD COVERED Final Report-July 1, 1975 - June 30, 1976
		6 PERFORMING ORG REPORT NUMBER
7 AUTHOR(s) Delbert Taylor and David A. Duesterhaus, ARO, Inc.		8 CONTRACT OR GRANT NUMBER(s)
9 PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center (DY) Air Force Systems Command Arnold Air Force Station, Tennessee 37389		10 PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 65807F
11 CONTROLLING OFFICE NAME AND ADDRESS Arnold Engineering Development Center(DYFS) Air Force Systems Command Arnold Air Force Station, Tennessee 37389		12 REPORT DATE September 1976
		13 NUMBER OF PAGES 33
14 MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15 SECURITY CLASS. (of this report) UNCLASSIFIED
		15a DECLASSIFICATION DOWNGRADING SCHEDULE N/A

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SUPPLEMENTARY NOTES

Available in DDC

19 KEY WORDS (Continue on reverse side if necessary and identify by block number)

diffusers
variable-area nozzles
test facilities
test equipment
exhaust diffuser
performance

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experimental development program was conducted to investigate the performance of a variable-area subsonic diffuser. The project goal was to improve the static pressure rise ratio of exhaust gas diffusers used with subsonic, high-bypass-ratio, front fan engines during direct-connect testing in ground test facilities. A one-tenth scale model of the TF-39 turbofan engine was used in the experiment. Diffuser performance data were

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20. ABSTRACT (Continued)

recorded during model engine operation with cold air at five simulated power settings with five diffuser configurations. Test cell and engine cowl surface pressures were recorded to determine the influence of the exhaust gas diffuser on these pressures. Data from all configurations were analyzed to determine the effect of the exhaust gas diffusers on test cell and engine cowl pressures and to determine the diffuser pressure rise ratio. Test cell and engine surface pressure data were not affected by the diffuser configuration. The static pressure rise ratio of one variable-area diffuser configuration tested exceeded that of all others and a conventional 5-deg half-angle subsonic diffuser.

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC) for the Directorate of Technology (AEDC) under Program Element 65807F. The results of the test were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Number R32P-A9A. The authors of this report were Delbert Taylor and David A. Duesterhaus, ARO, Inc. The data analysis was completed on April 30, 1976, and the manuscript (ARO Control No. ARO-ETF-TR-76-75) was submitted for publication on July 16, 1976.

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1.0 INTRODUCTION

Aerospace propulsion ground test facilities employ diffusers using the momentum of the propulsion system exhaust jet to increase the pressure at the inlet to the test facility exhaust gas pumping system. This effects an increase in the pressure-simulated test altitude capability of the facility, or a decrease in the required compressor pressure ratio and associated power. The efficient diffusion of a supersonic jet requires a supersonic diffusion section having a minimum area (throat) whose size is determined by the aerothermodynamic characteristics of the jet. The supersonic section is followed by a subsonic diffuser having an exit diameter equivalent to approximately twice its inlet (throat) diameter. Since the jet characteristics vary with engine power setting, the throat of the diffuser should, for maximum efficiency, also vary with power setting. Therefore, a variable-area diffuser was developed for use with supersonic jets (Refs. 1 and 2). The performance of this diffuser exceeded that of the fixed-area diffusers currently in use.

The size and complexity of the variable-area diffuser normally required to match specific engines, makes frequent replacement undesirable. Therefore, it is prudent to equip each test cell with a variable-area diffuser sized to test the largest engine that the cell can accommodate and change only the diffuser inlet as required to match the test engines.

The most severe performance requirement for the variable-area supersonic diffuser occurs during tests of subsonic high-bypass-ratio turbofan engines. Thus, the investigation reported herein evaluated the performance characteristics of the supersonic variable-area diffuser with a model of a TF-39 engine, a high-bypass-ratio turbofan engine, whose exhaust jet is subsonic.

2.0 APPARATUS

2.1 TEST CELL AND ENGINE INSTALLATION

The test cell with the model TF-39 engine installed is shown in Fig. 1. The test cell was comprised of two sections of 20-in.-diam duct, 39 and 43.75 in. long, for a total test cell length of 82.75 in.

The upstream end of the test cell was sealed with a flat plate welded to a 10-in.-diam section that supported the 10-in. inlet duct from the ETF air supply plant. The downstream end of the test cell was also sealed with a flat plate which supported the various diffuser installations. The test cell was designed to be a 1/10th-scale model of the Propulsion Development Test Cell (J-1). A 1/10th-scale simulator of the TF-39 engine (shown in Fig. 2) was mounted concentric with the test cell and secured to the upper test cell wall. The engine inlet was connected to the 10-in. air supply duct and sealed to prevent any leakage into the test cell. The fan exit diameter is 9.5 in.

2.2 DIFFUSER CONFIGURATIONS

Five diffuser configurations, four of which were of the variable-area design, were experimentally evaluated. The pertinent dimensions of each configuration are summarized in Table 1.

2.2.1 Configurations 1, 2, and 3

Diffuser configurations 1, 2, and 3 have throat diameters 0.966 times the engine fan exit diameter. The throat diameter (D_d) was determined from the experiments performed in Ref. 3. Configuration 1 (depicted in Fig. 3) consisted of a converging conical inlet, a constant diameter throat section, and a conical exit section which contained a translating plug for varying the throat area. The total diffuser length to fan diameter ratio was 5.06. The conical diffuser centerbody was mounted concentric with the diffuser ducting. The diffuser exhausted into the 24-in.-diam exhaust duct which was connected to the ETF exhaust plant. The distance from the diffuser inlet plane to the rear of the engine plug (X) (see Fig. 1) was 0.738 fan diameters. The inlet to the diffuser is required to efficiently capture the engine flow to prevent recirculation of the exhaust gases into the test cell.

Configuration 2 differed from configuration 1 in that the centerbody base diameter was increased from 8 in. to 9.2 in. by the addition of a short extension.

Configuration 3 was derived from configuration 2 by removing the 16-in.-long, 9.2-in.-diam cylindrical section. Thus, the converging inlet attached to the diverging exit resulted in a total diffuser length-to-fan diameter ratio (L/D_{fe}) of only 3.38, the shortest configuration tested.

2.2.2 Configuration 4

Variable-area diffuser configuration 4 is depicted in Fig. 4. The configuration consisted of a 30-deg conical inlet, a constant diameter throat section, a 7.33-deg half-angle exit cone, and a traversing conical plug. The constant diameter inlet, constructed from standard pipe, was tested to determine the effect of increasing the throat area on diffuser performance. The throat diameter is 1.09 times the engine fan exit diameter. The centerbody used in configuration 2 was modified by increasing the base diameter to 10.0 in. The total length of configuration 4 is 4.44 engine fan exit diameters. The distance from the engine plug to the inlet plane (X) is 0.58 fan diameters.

2.2.3 Configuration 5

The cylindrical diffuser, configuration 5 (shown in Fig. 5) was used for initial checkout of the test cell and engine installation. The 10.4-in.-diam duct was fabricated from standard pipe with a 30-deg conical inlet and a total length of 5.25 fan diameters. The diffuser inlet plane location (X) was 0.58 fan diameters downstream of the engine plug.

2.3 INSTRUMENTATION

A temperature and an inlet total pressure rake were installed in the 10-in. inlet ducting (see Fig. 1). The inlet total pressure probe arrangement is depicted in Fig. 6. The inlet total pressure and temperature data were used to set test conditions which were essentially identical for each test. The test cell pressure was measured at the four stations and angular locations shown in Fig. 7. The exhaust pressure was measured in the exhaust ducting as shown in Fig. 1. The engine surface pressure orifice locations are depicted in Figs. 8 and 9, and the fan exit total pressure probe location is shown in Fig. 2.

3.0 PROCEDURE

3.1 GENERAL

Tests of each diffuser configuration were initiated by evacuating the test cell and conducting a vacuum pressure check. After an air-tight installation was verified, the air supply isolation valves were opened to establish airflow at the desired pressure and temperature conditions upstream of the model engine. The simulated engine conditions were defined from the model engine calibration (Ref. 4) and by the actual TF-39 engine tests. The exhaust pressure was then adjusted to simulate the test cell pressure. A summary of the test conditions is given in Table 2. Once steady-state conditions were established, the data systems were sequenced to record the data. Signals from pressure and temperature sensors were recorded on magnetic tape for later computer reduction to engineering units. Each pressure probe was connected to a pressure transducer using a 12-element scanner valve. The pressure transducers were calibrated before and after each test by impressing several known pressures, measured with a secondary standard, on each transducer.

3.2 DATA MEASUREMENT UNCERTAINTY

The uncertainty of the data measurement was calculated using a confidence level of 95 percent by the procedure defined in Ref. 5. The uncertainty for all the pressure parameters is ±0.6 percent of the reading. The uncertainty in pressure ratio is ±0.85 percent of the value. The uncertainty value contains the errors from the transducer and the electrical data recording and data processing systems.

4.0 RESULTS AND DISCUSSION

4.1 DIFFUSER CONFIGURATIONS 1, 2, AND 3

Diffuser performance is measured by the static pressure rise from the inlet to the exit of the diffuser ($P_{ex}/\overline{P}_c$). The diffuser performance is presented herein versus the fan exit pressure ratio ($P_{t_{fe}}/\overline{P}_c$) which is indicative of the engine power setting. Configurations 1, 2, and 3 are small variations of the basic 0.966 D_d/D_{fe} diffuser configuration and thus have similar performance as shown in Fig. 10. The pressure rise ratio of configuration 1 exceeded that of configurations 2 and 3 by a maximum of 2 percent. The performance of a conventional subsonic diffuser (5-deg half-angle, area ratio 4, D_d = 9.6 in.) from Ref. 3, depicted by the dashed line in Fig. 10, exceeded that of configurations 1, 2, and 3 by approximately 6 percent. The poorer performance of configurations 1, 2, and 3 probably results from a slightly larger contraction loss associated with the 9.2-in.-diam inlet.

The effect of decreasing the minimum area of configuration 2 by moving the conical centerbody toward the diffuser inlet is shown in Fig. 11. A 2-in. movement of the centerbody, causing a 3.26-percent decrease in diffuser minimum area, resulted in approximately a 4-percent decrease in pressure rise ratio ($P_{ex}/\overline{P}_c$). Since the function of the diffuser is to maximize $P_{ex}/\overline{P}_c$ for all test conditions, the centerbody should not be moved into the diffuser throat for the subsonic test conditions.

4.2 DIFFUSER CONFIGURATIONS 4 AND 5

The pressure rise ratio ($P_{ex}/\overline{P}_c$) for configurations 4 and 5 is presented in Fig. 12. The static pressure rise ratio of the variable-area diffuser (configuration 4) at $P_{t_{fe}}/\overline{P}_c$ of 2.33 exceeded that of the cylindrical diffuser (configuration 5) by approximately 7 percent and also exceeded that of the conventional diffuser of Ref. 3 at values of fan nozzle pressure ratio greater than 1.6. The superior performance of configuration 4 is attributed to its larger diffuser inlet diameter which resulted in a smaller flow contraction loss.

The effect of moving the conical centerbody toward the diffuser inlet is shown in Fig. 13. A 3-in. movement of the centerbody from y = 1.8 to 4.8, causing a 4.92-percent decrease in diffuser minimum area, resulted in a 3-percent decrease in the pressure rise. Further movement of the centerbody (Y > 8.8 in.) caused further decreases in diffuser performance until eventually the inlet static pressure, and thus test cell ambient pressure, began to increase. The maximum performance of the diffuser occurred when the conical centerbody was moved completely out of the cylindrical section (Y = -1.2 in.). The same effect was seen for configuration 2 (Fig. 11). Thus, while the moveable centerbody is needed to maximize the diffuser performance for supersonic operation (Ref. 2) it is a detriment for subsonic operation unless positioned such that $Y \leq 0$.

4.3 EFFECT OF DIFFUSERS ON TEST CELL, CORE ENGINE COWL, AND EXHAUST NOZZLE PLUG SURFACE PRESSURES

The axial variation of the test cell static pressure is shown in Fig. 14. The circumferential variation of the cell pressure at each axial location (see Fig. 7) was within the symbol size shown in Fig. 14 and, therefore, is not presented. Although the axial distribution of the cell pressure is a function of $P_{tf_e}/\overline{P}_c$, it is independent of the diffuser configuration and agrees well with the data from Ref. 3.

The pressures measured on the engine simulator are presented in Fig. 15 for various values of $P_{tf_e}/\overline{P}_c$. The characteristic shape of the lines depicting the data of Ref. 3 in Figs. 15a, b, and c was taken from Ref. 4 and is the result of alternate expansion and compression waves in the fan exhaust flow at values of $P_{tf_e}/\overline{P}_c$ greater than about 1.9. Slight variation in $P_{tf_e}/\overline{P}_c$ can cause an appreciable variation in the location of the wave impingement point on the cowl surface. Thus, it is not surprising to encounter some data scatter near the fan exit station. Further downstream, particularly on the exhaust nozzle plug, the pressures are independent of the diffuser configuration for all conditions investigated.

5.0 SUMMARY OF RESULTS

The results of the experimental study to determine the performance of variable-area diffusers for test cells with high-bypass-ratio subsonic turbofan engines are:

1. The pressure rise ratio obtained with the variable-area diffuser, which had a throat diameter 1.092 times the engine fan diameter (configuration 4), exceeded that of the other configurations having throat diameter 0.966 times the engine fan diameter and of the conventional 5-deg half-angle subsonic diffuser used in Ref. 3.

2. The maximum value of the pressure rise ratio for the variable-area diffuser configurations occurred with the apex of the centerbody positioned downstream of the plane of the diverging diffuser inlet so that no constriction occurred in the constant-area portion of the diffusers.

3. The variable-area diffusers did not affect the engine surface pressure distribution.

REFERENCES

1. Taylor, Delbert, Simmons, Marvin, and Duesterhaus, David A. "Diffuser Studies." AEDC-TR-73-198 (AD774019), November 1973.
2. Taylor, Delbert, and Duesterhaus, David A. "Variable-Area Ejector Development." AEDC-TR-76-97
3. Taylor, Delbert, Simmons, Marvin, and Lee, Frank T. "Experimental Study of the Effect of Subsonic Exhaust Gas Diffusers on the Test Cell Wall and TF39 Cold-Flow Model Engine Exhaust Nozzle Plug and Core Engine Cowl Surface Pressures." AEDC-TR-73-13 (AD759177), April 1973.
4. Aircraft Engine Group. "Aerodynamic Model Test Report (Engine), 1/10-Scale Model Exhaust System Static Performance, TF39 Engine for C-5A Aircraft." G.E. No. 6DT006A03, February 14, 1968.
5. Abernethy, R. B., Pratt & Whitney Aircraft, and Thompson, J. W., Jr., ARO, Inc. "Handbook, Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD755356), February 1973.

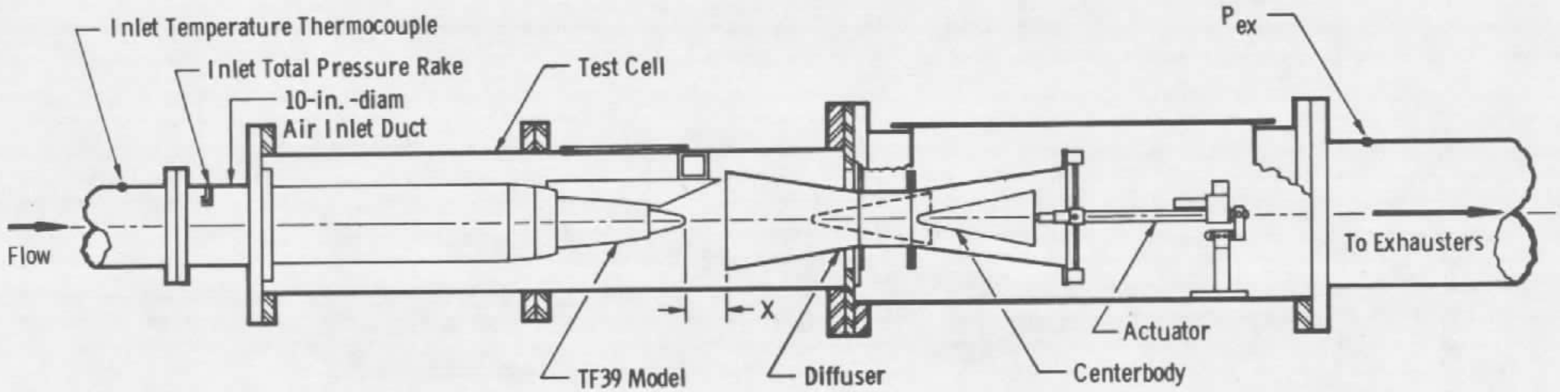


Figure 1. Typical test installation for the variable-area diffuser study.

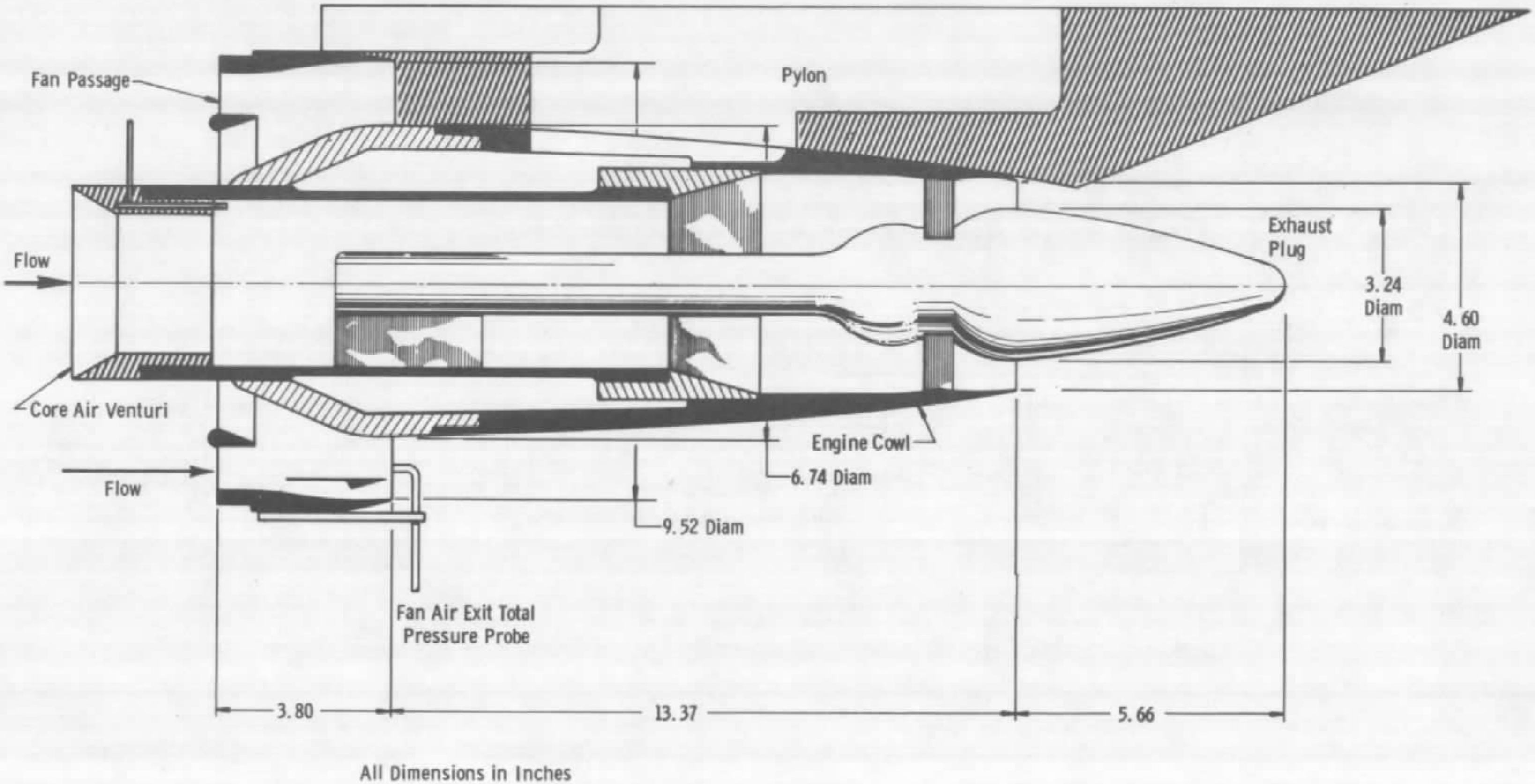


Figure 2. TF-39 model engine.

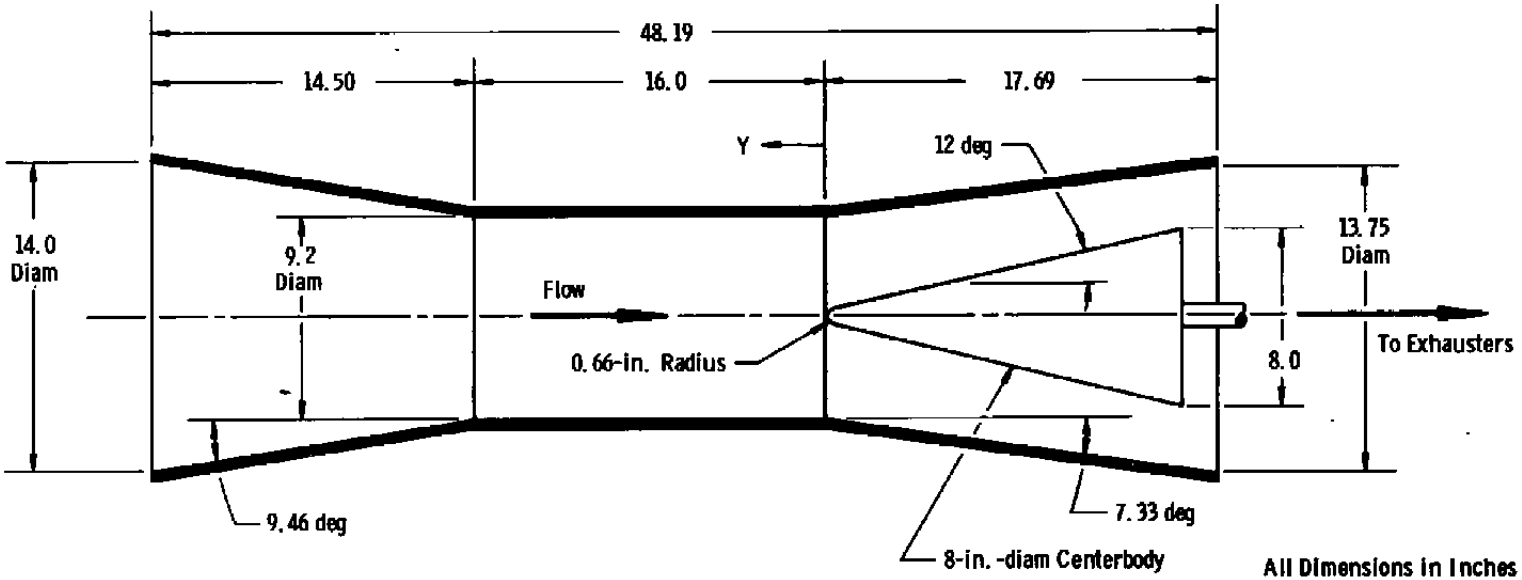


Figure 3. Diffuser configuration 1.

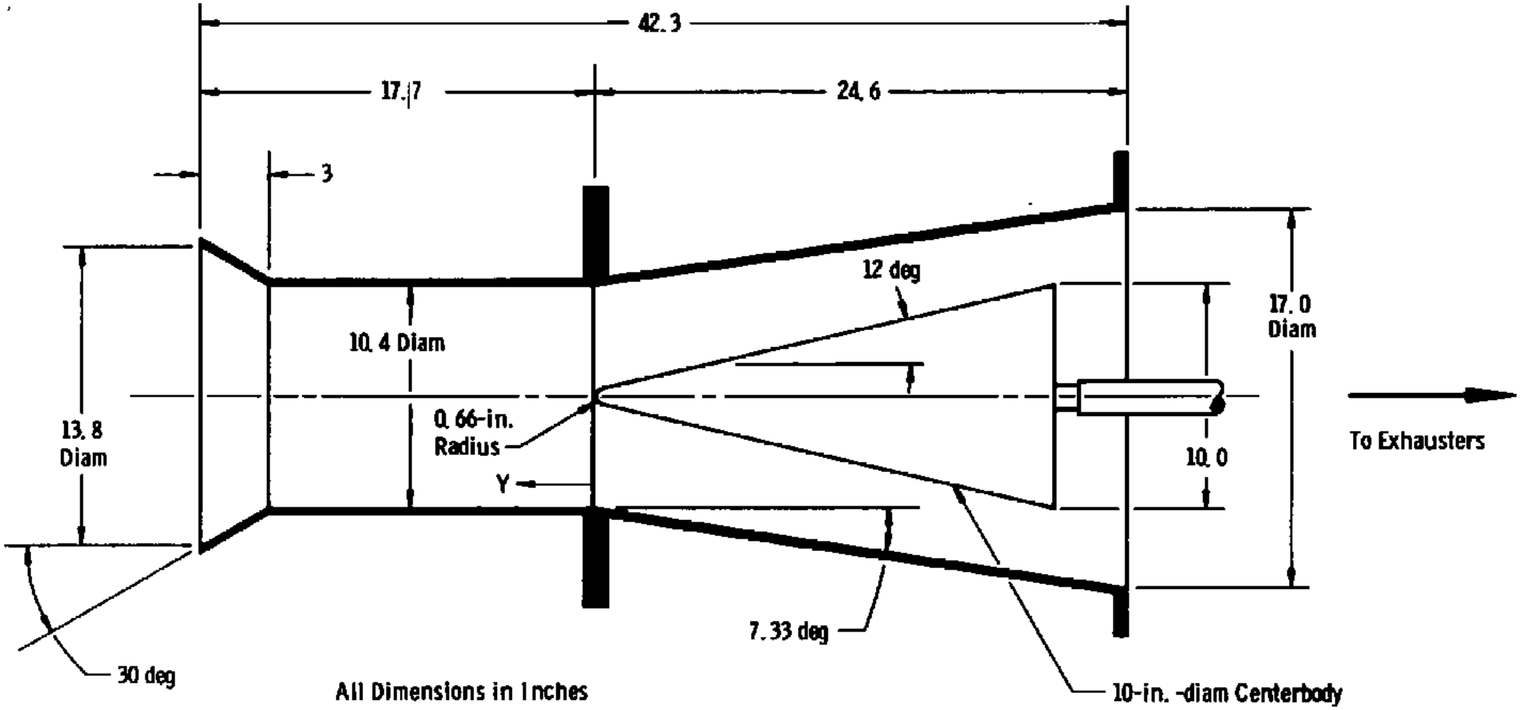


Figure 4. Diffuser configuration 4.

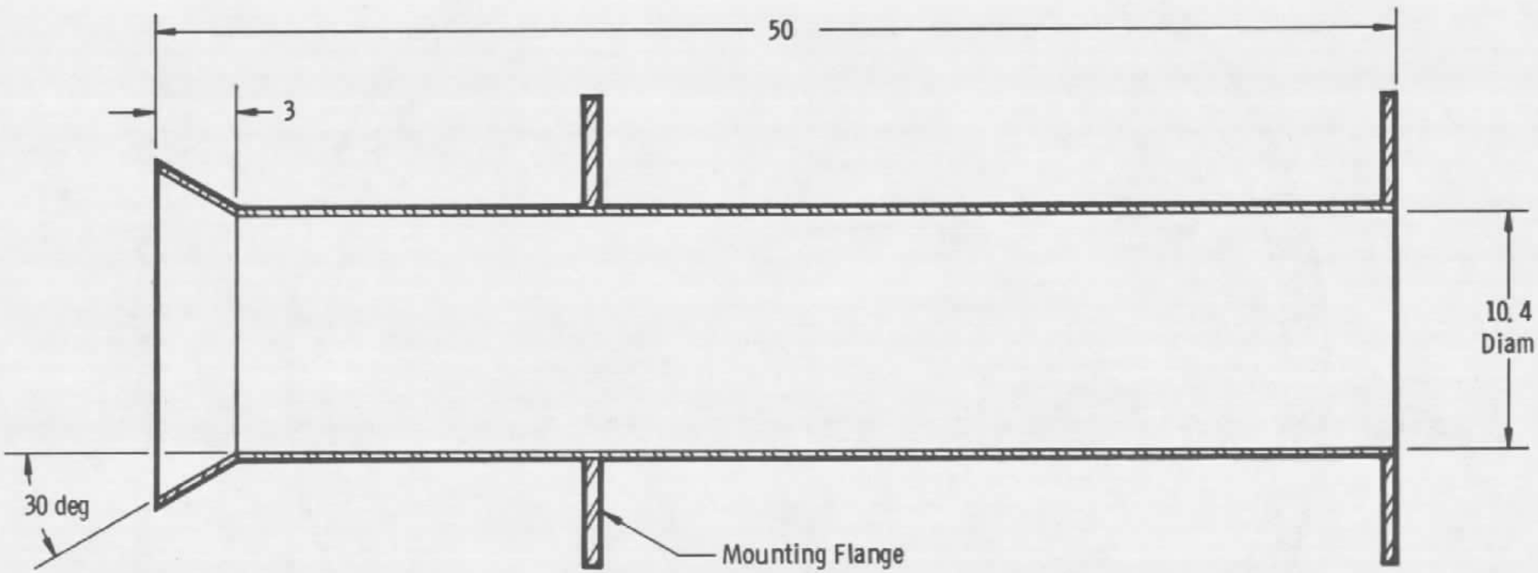


Figure 5. Diffuser configuration 5.

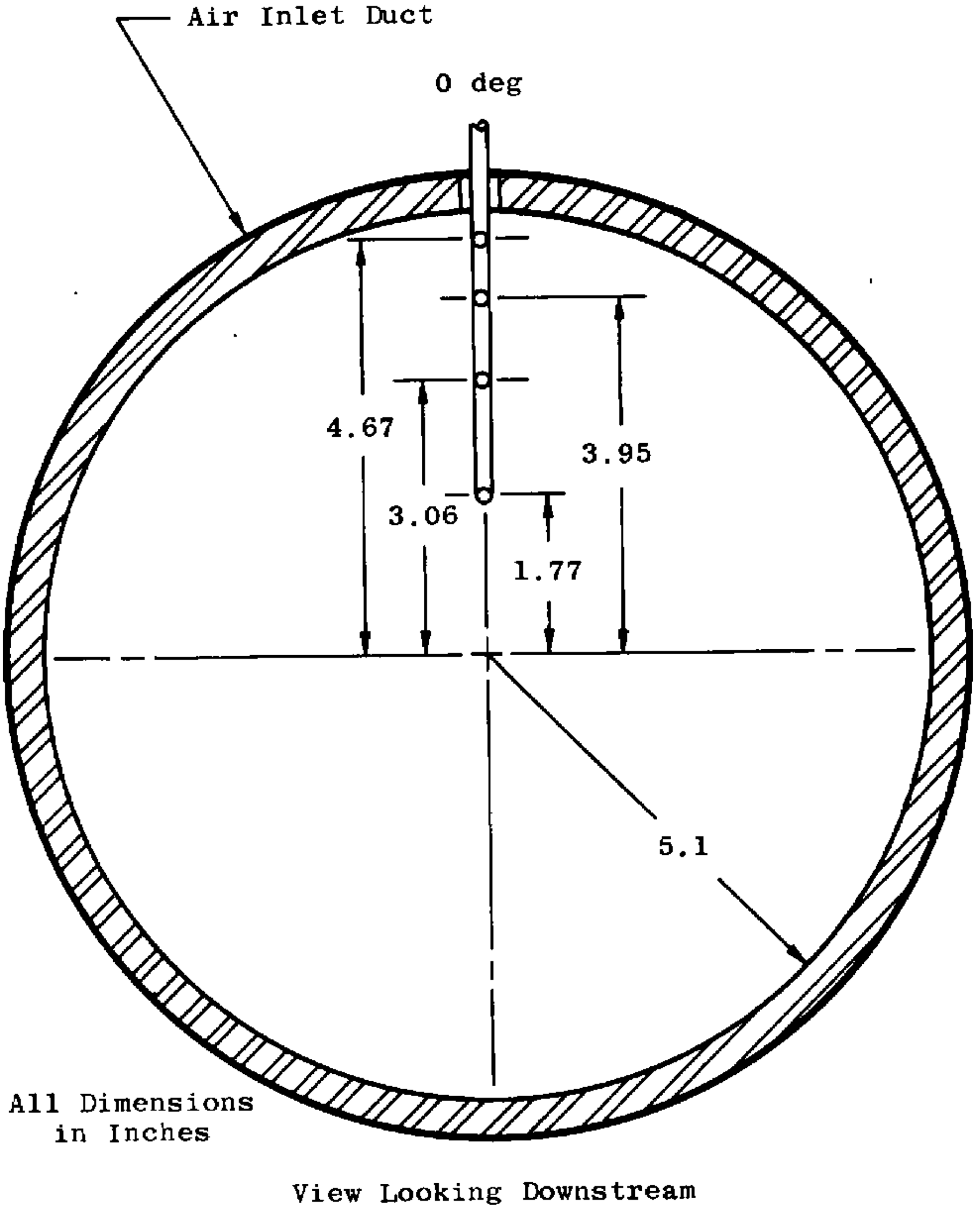


Figure 6. Inlet total pressure probe.

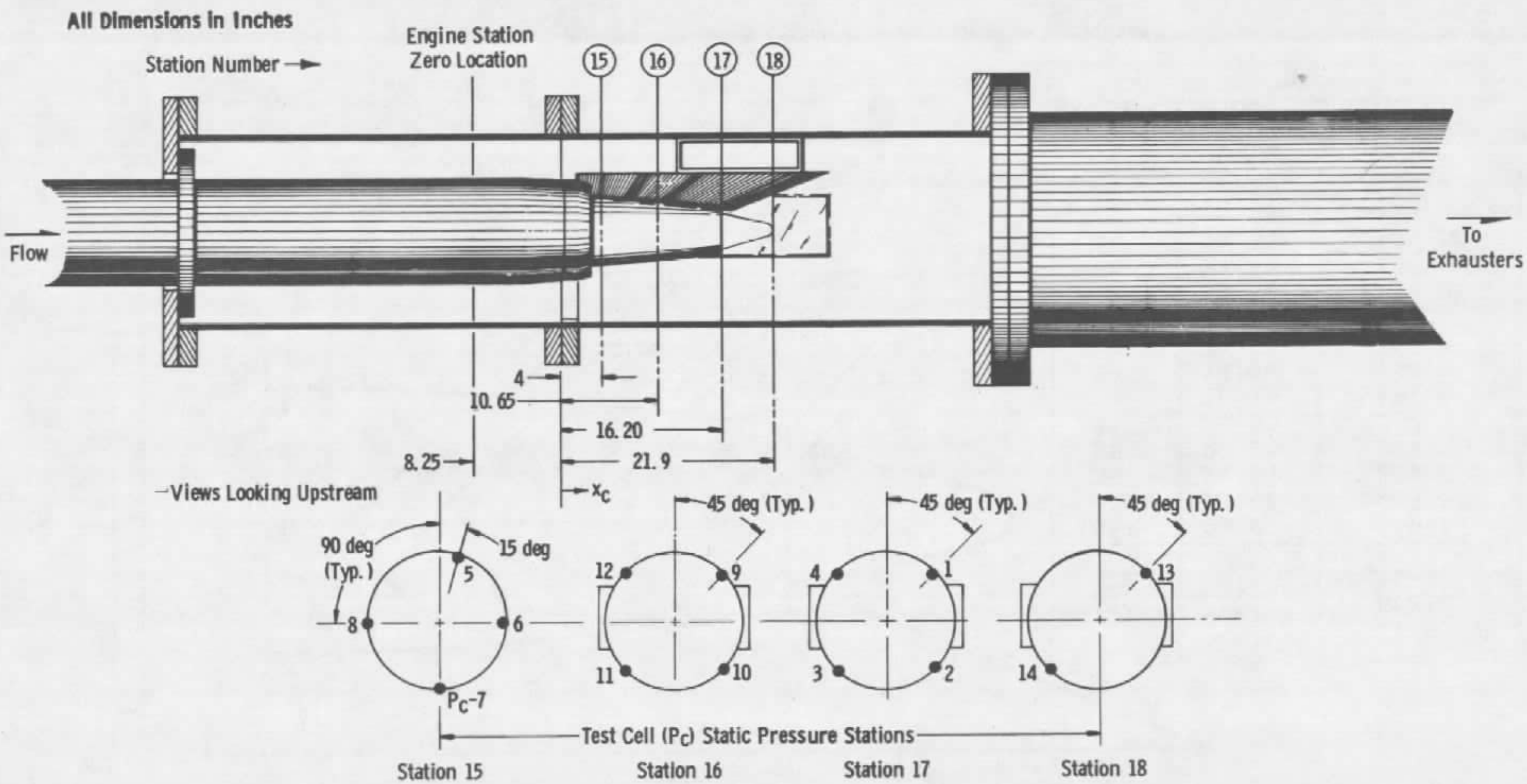
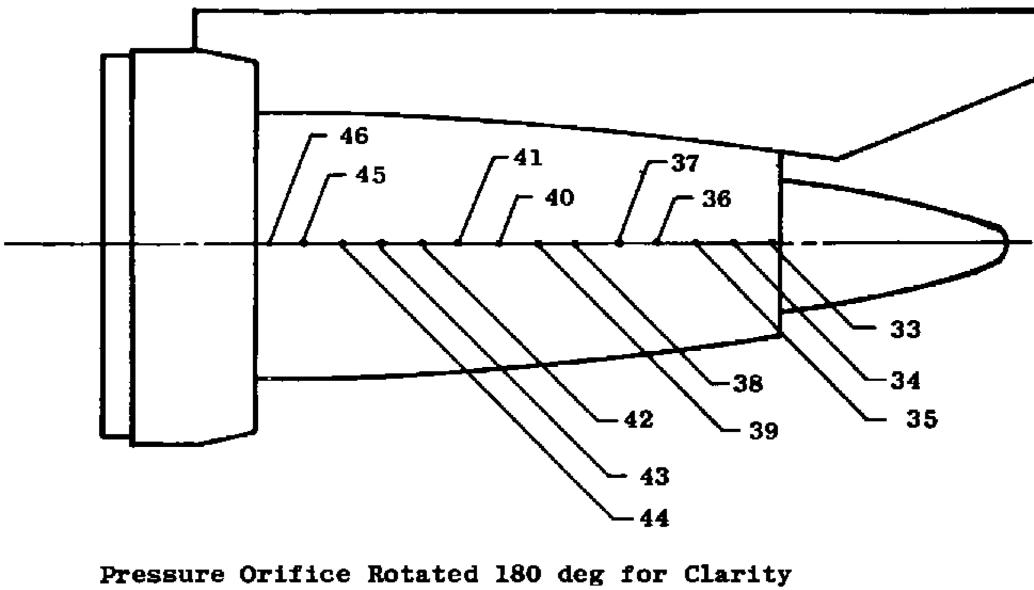


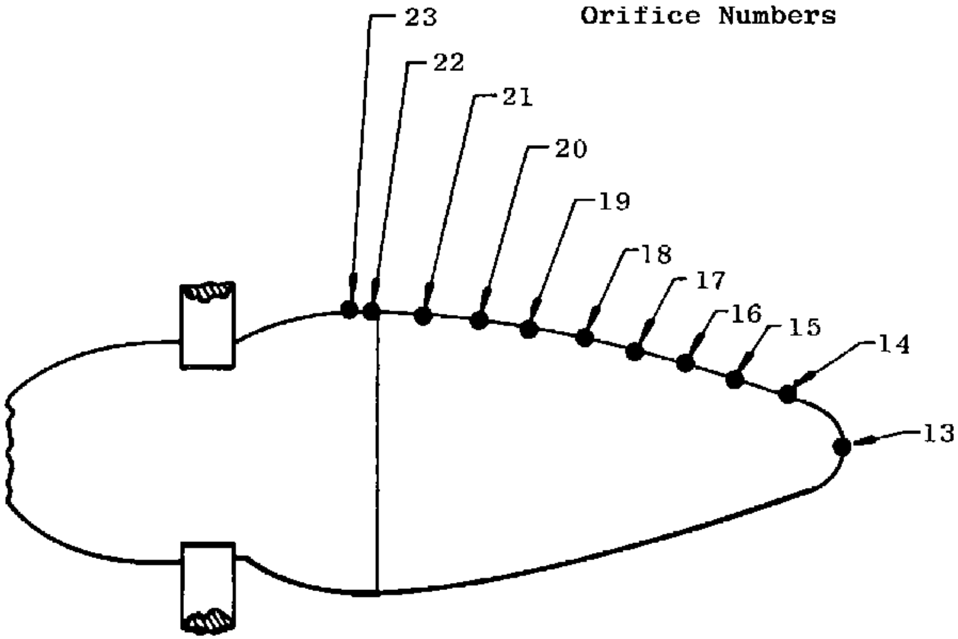
Figure 7. Test cell wall pressure orifice locations.



Orifice No.	Model Engine Station, in.	Full-Scale Engine Station, in.
33	23.85	238.5
34	22.85	228.5
35	21.85	218.5
36	20.95	209.5
37	20.05	200.5
38	19.15	191.5
39	18.00	180.0
40	17.30	173.0
41	16.25	162.5
42	15.30	153.0
43	14.40	144.0
44	13.55	135.5
45	13.05	130.5
46	12.50	125.0

Engine Station Zero Location Shown in Fig. 7

Figure 8. Model TF-39 cowl static pressure orifice locations.



Orifice No.	Model Engine Station, in.	Full-Scale Engine Station, in.
13	30.15	30.15
14	29.55	295.5
15	29.05	290.5
16	28.45	284.5
17	27.80	278.0
18	27.05	270.5
19	26.35	263.5
20	25.55	255.5
21	25.05	250.5
22	24.70	247.0
23	24.60	246.0

Engine Station Zero
Location Shown in Fig. 7

Figure 9. Model TF-39 exhaust plug static pressure orifice locations.

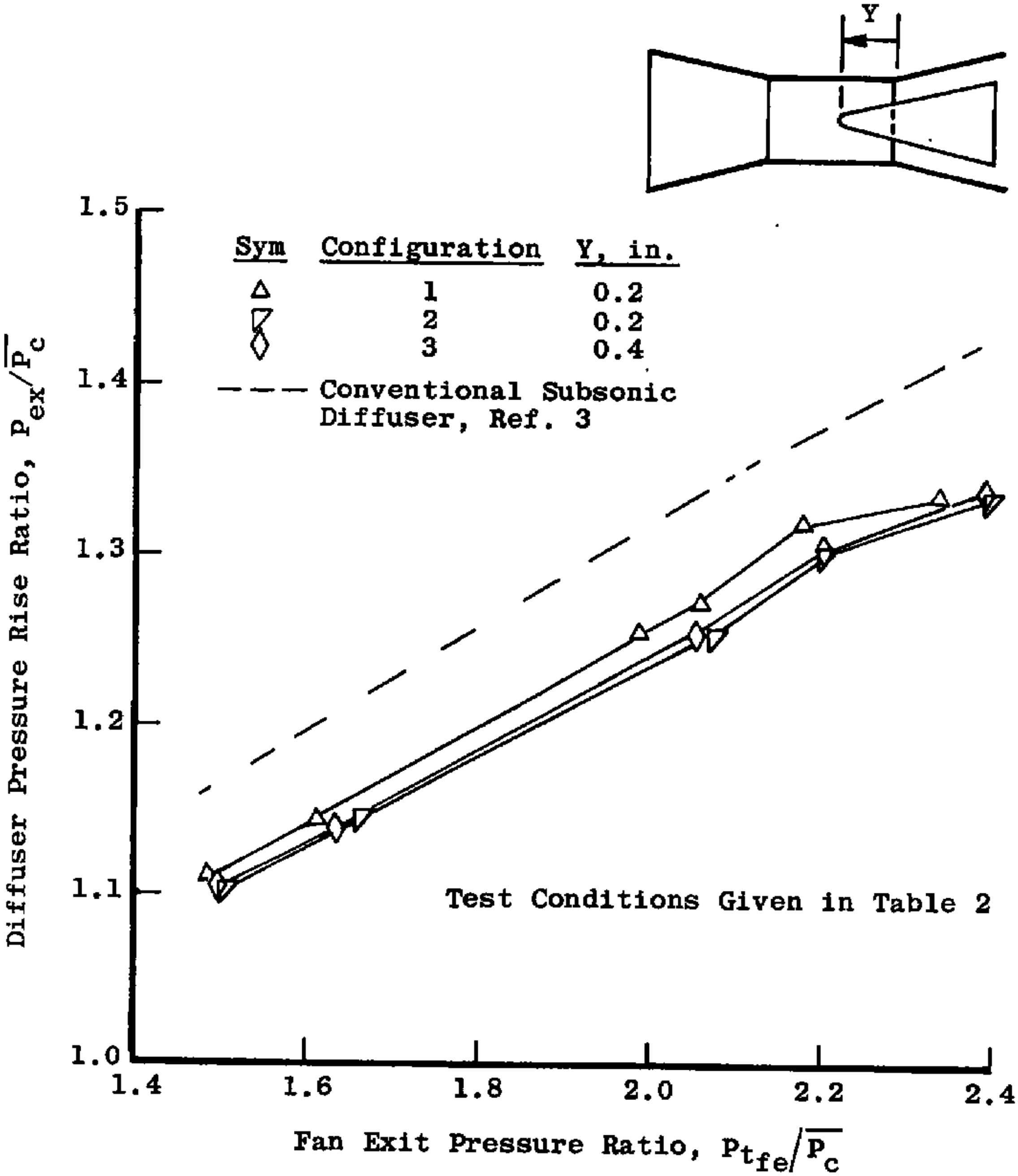


Figure 10. Performance of variable-area diffuser configurations 1, 2, and 3.

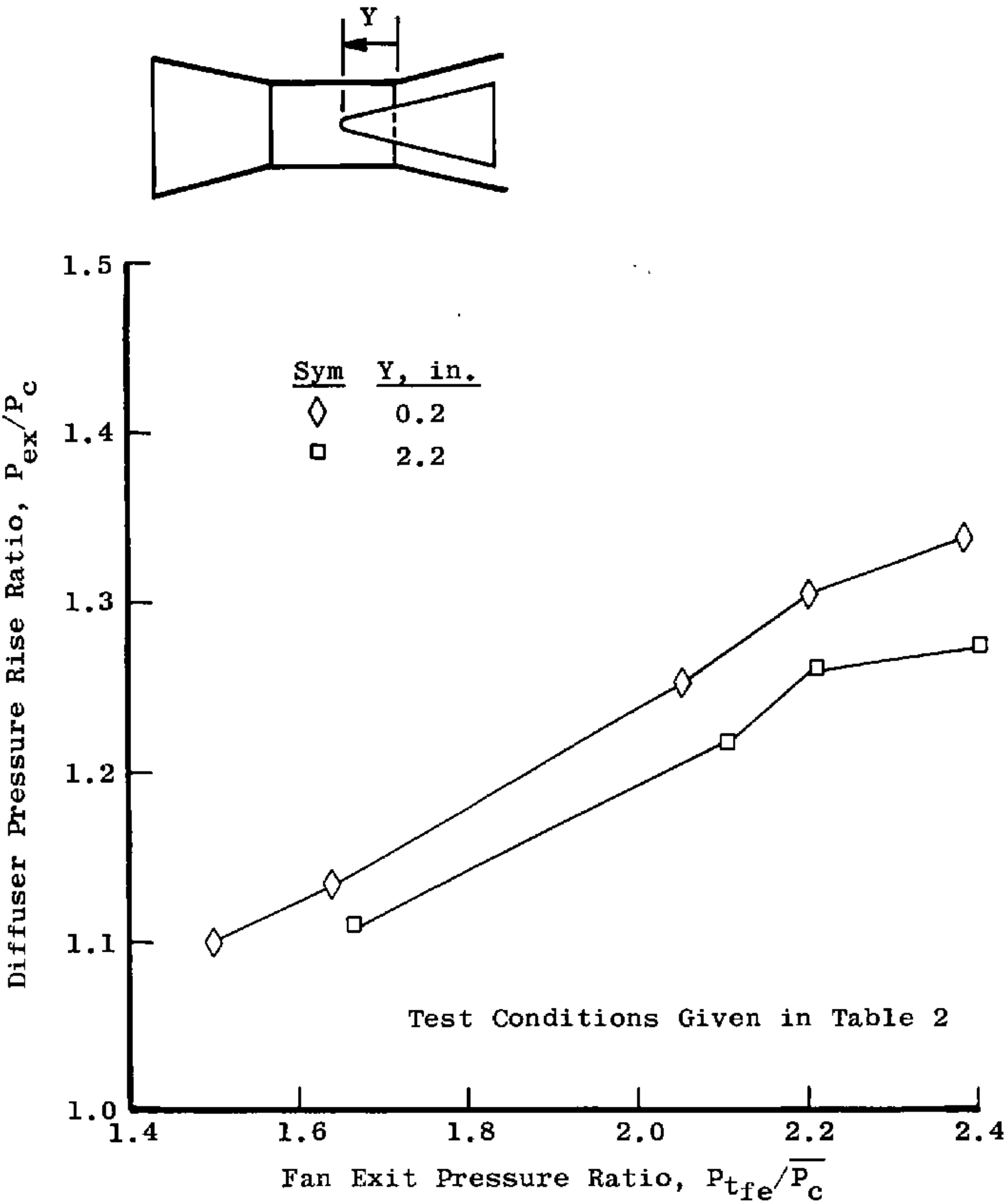


Figure 11. Effect of centerbody position on diffuser configuration 2.

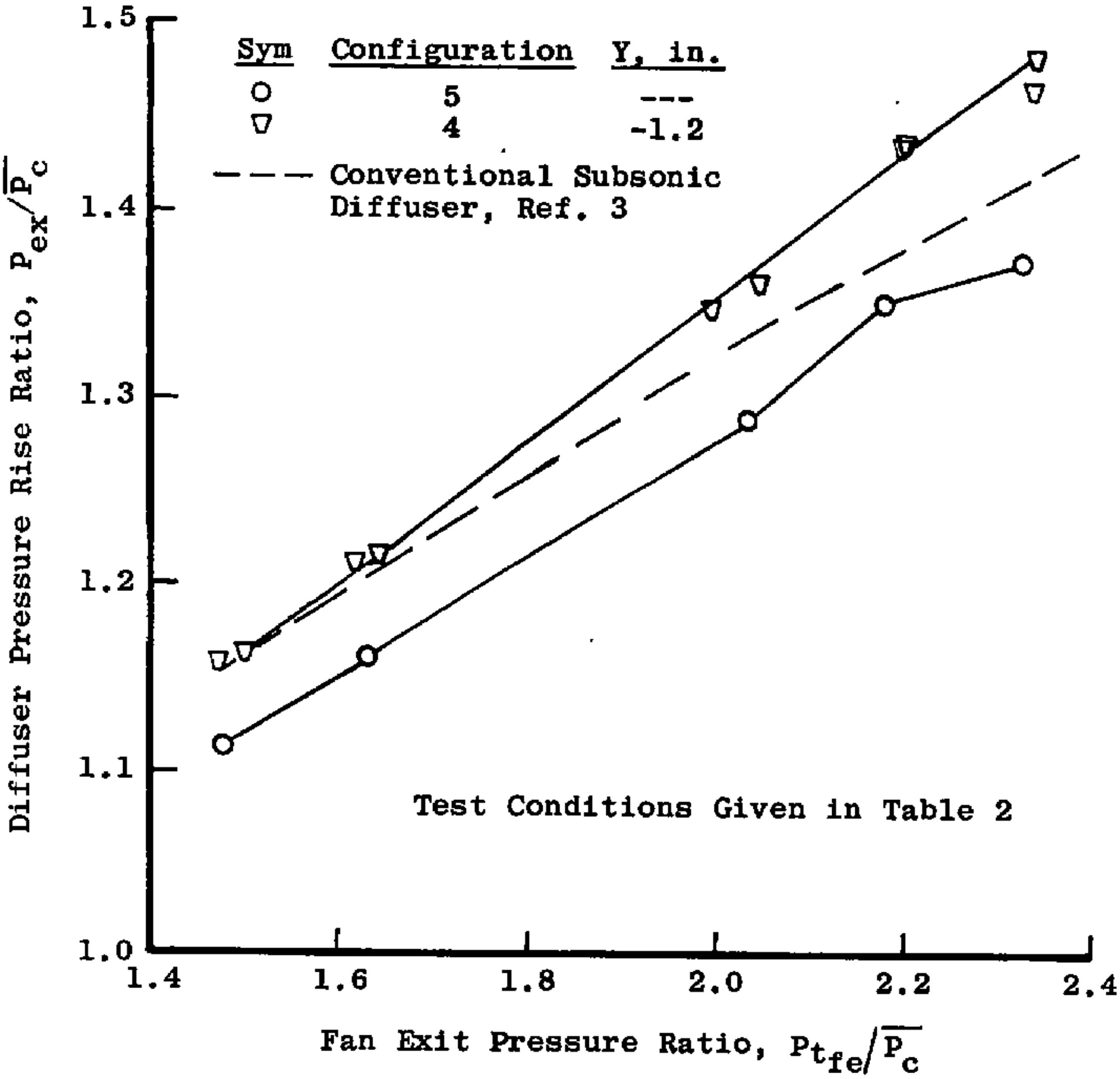


Figure 12. Performance of diffuser configurations 4 and 5.

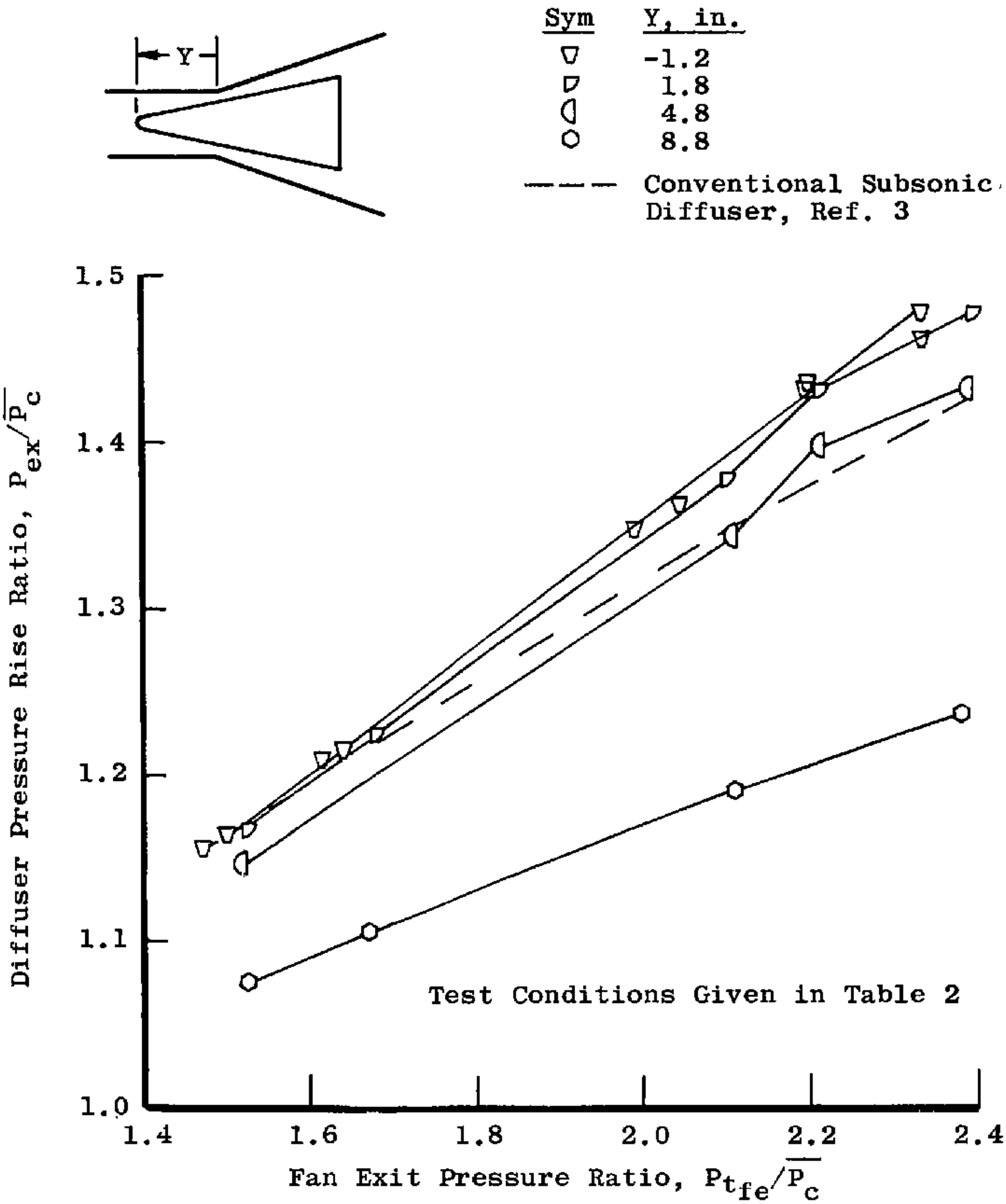


Figure 13. Effect of centerbody position on diffuser configuration 4.

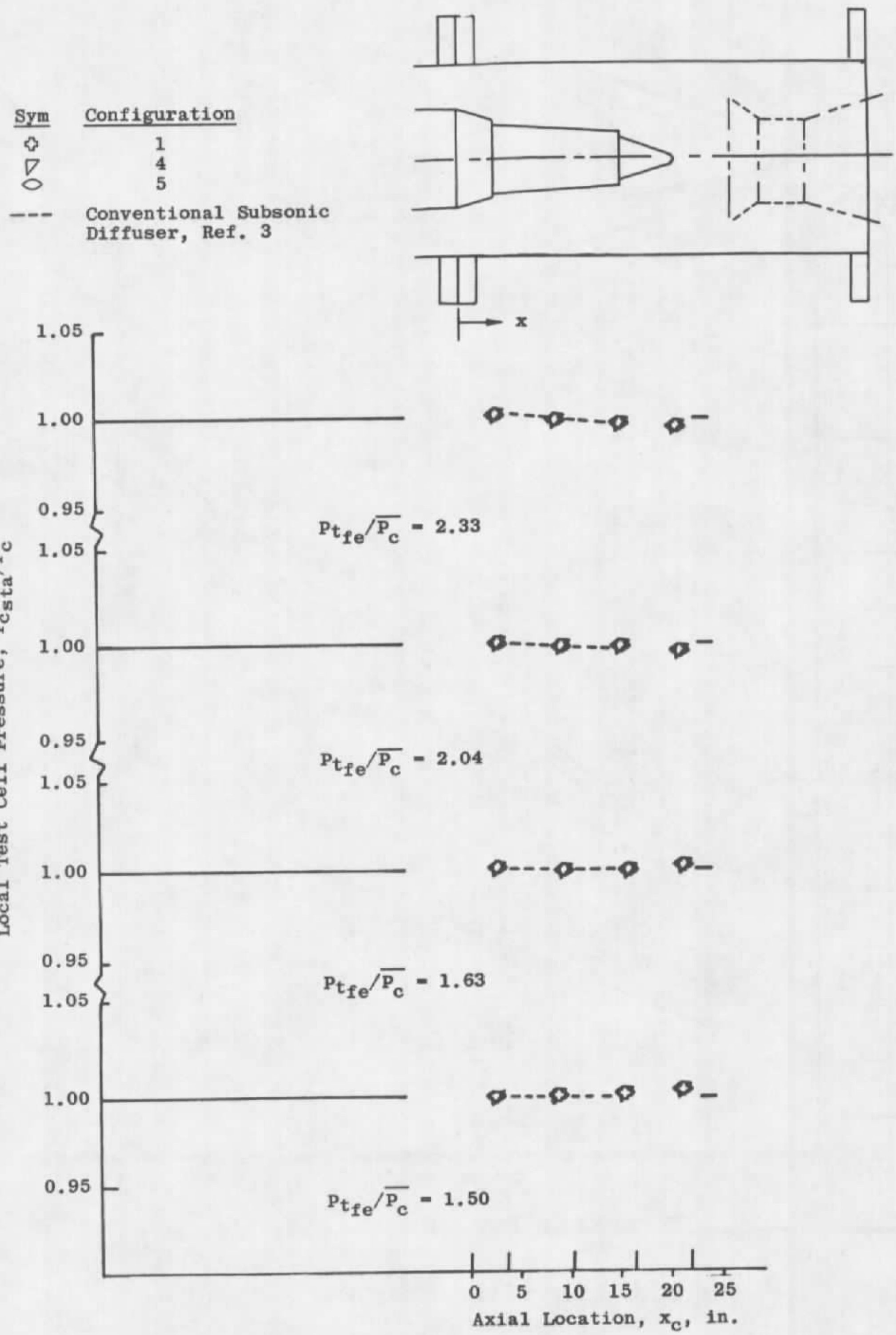
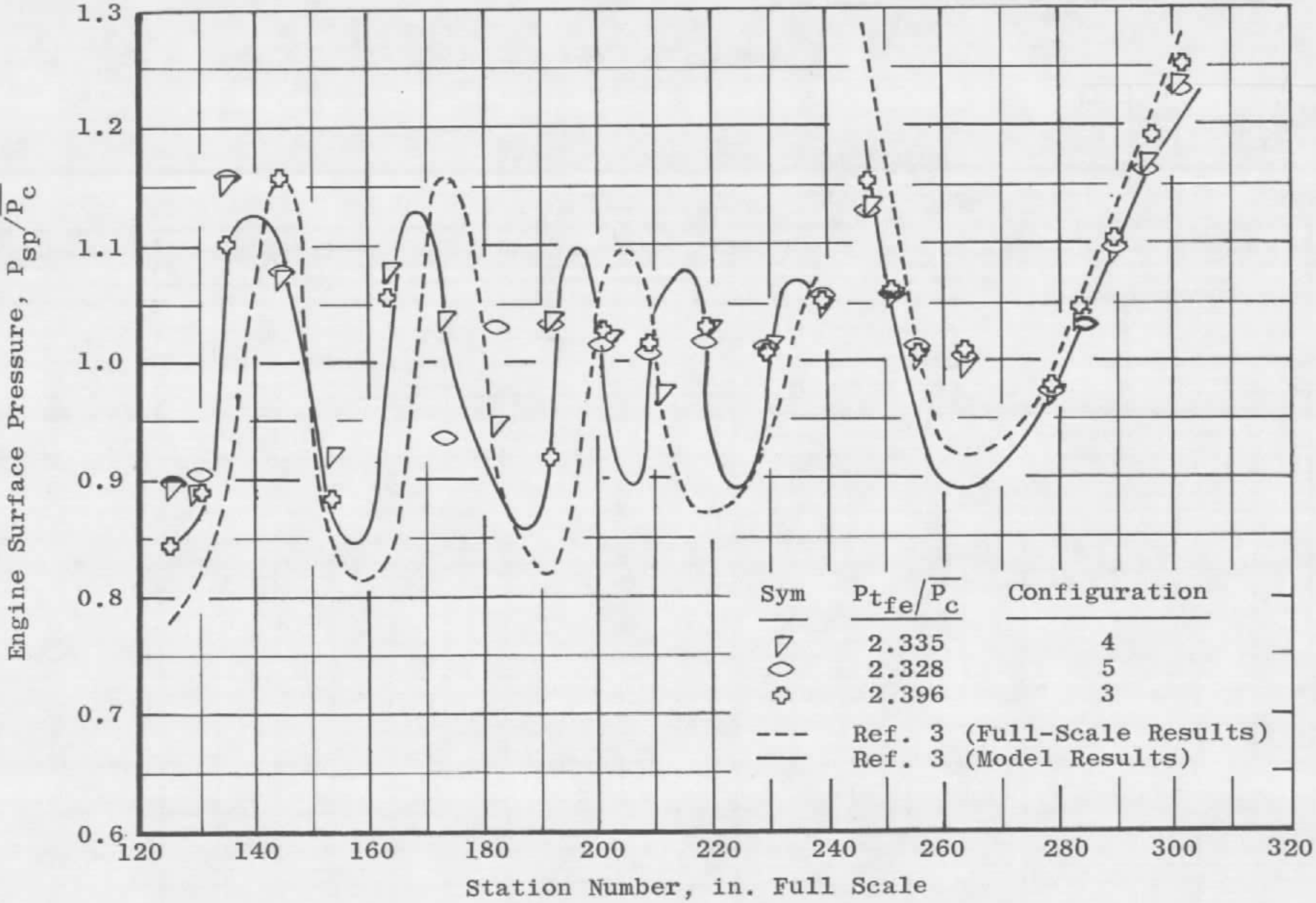
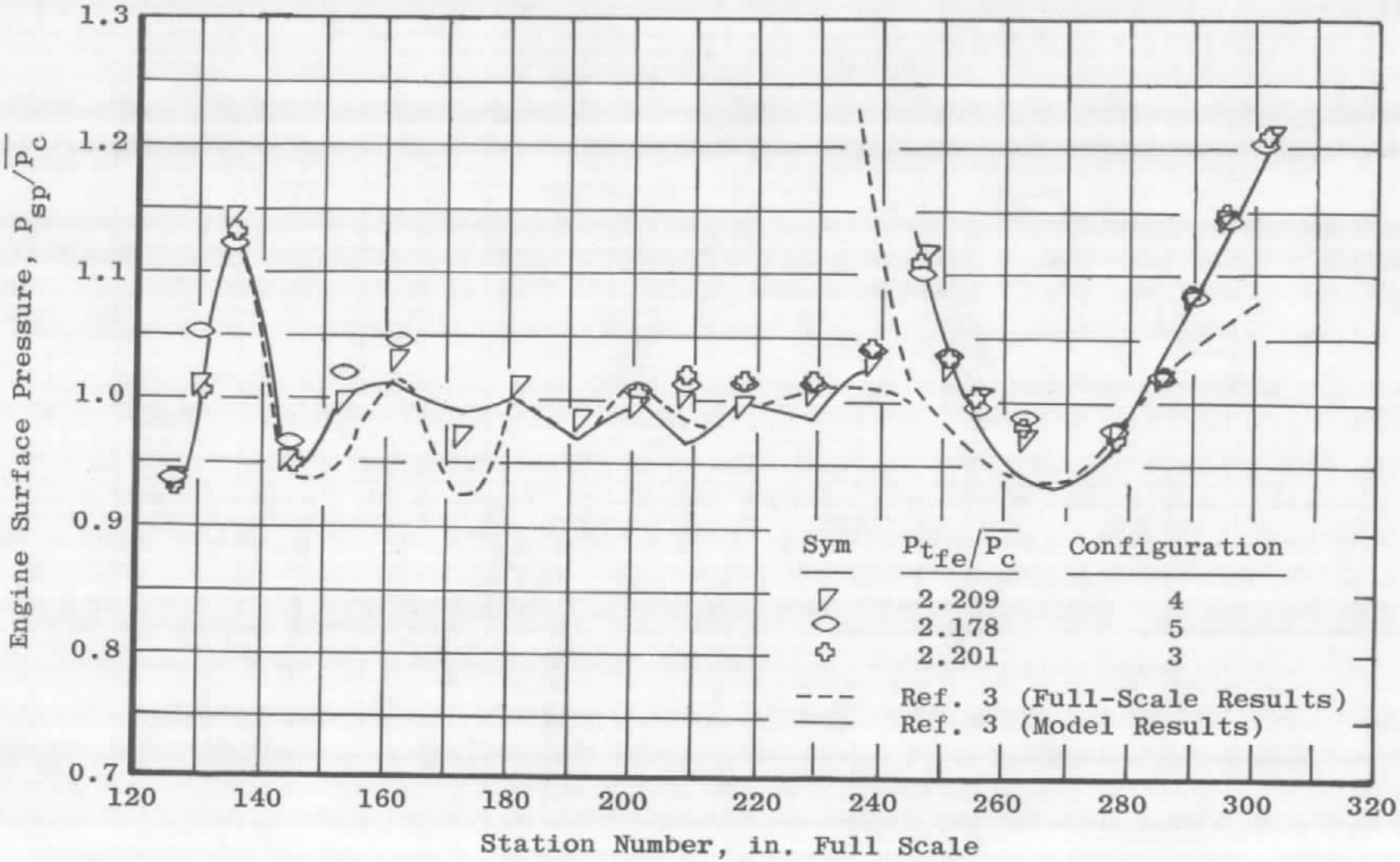


Figure 14. Axial variation of test cell pressure.



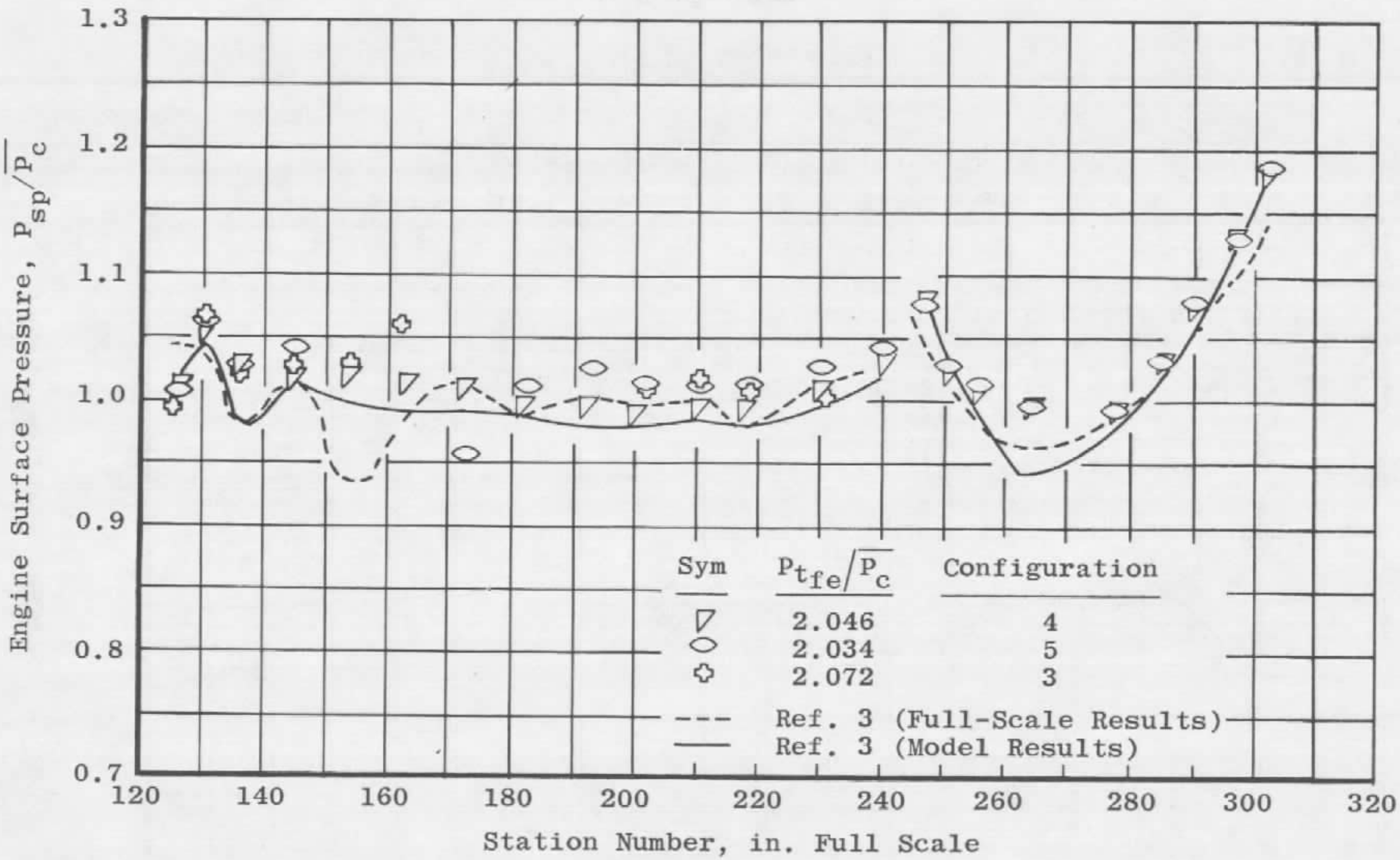
a. $P_{t_{fe}}/\overline{P}_c = 2.34$

Figure 15. Turbofan engine surface pressure.

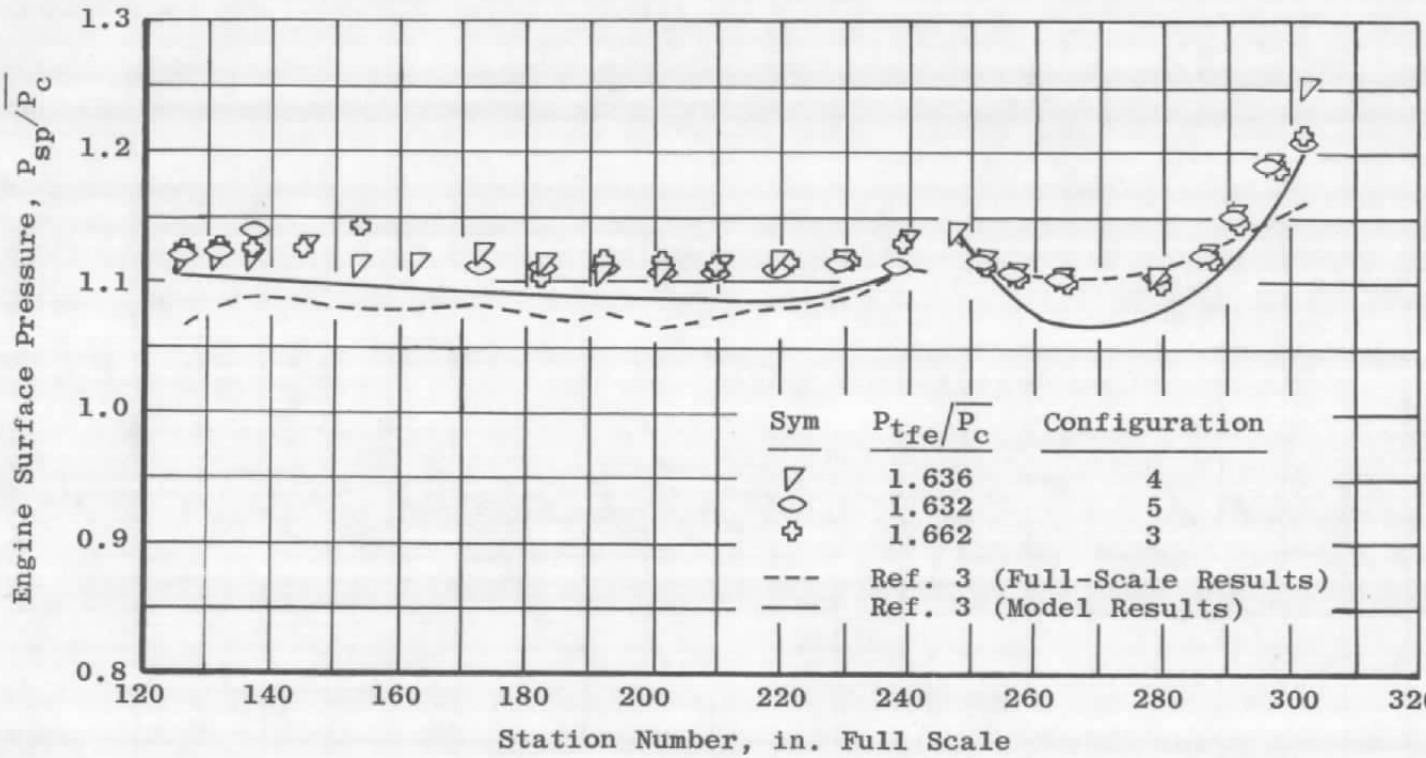


b. $P_{t_{fe}}/\overline{P}_c = 2.20$

Figure 15. Continued.

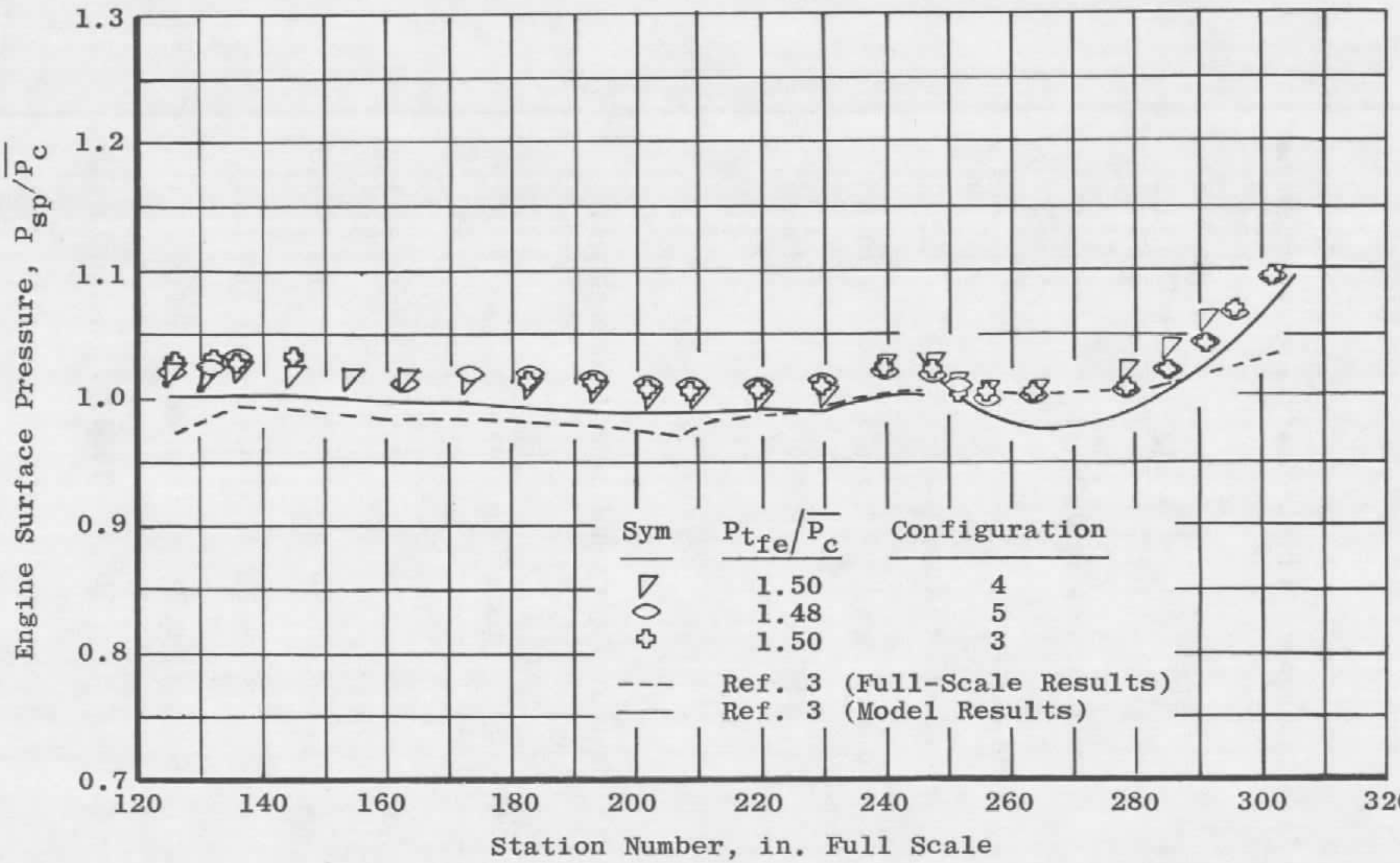


c. $P_{t_{fe}}/\overline{P}_c = 2.04$
Figure 15. Continued.



d. $P_{t_{fe}}/\overline{P}_c = 1.60$

Figure 15. Continued.



e. $P_{t_{fe}}/\overline{P}_c = 1.47$
Figure 15. Concluded.

Table 1. Summary of the Diffuser Configurations Studied

Configuration Number	Type	D_d/D_{fe}	Centerbody Base Diameter, in.	L/D_{fe}
1	Variable Area	0.966	8.0	5.06
2	Variable Area	0.966	9.2	5.06
3	Variable Area	0.966	9.2	3.38
4	Variable Area	1.090	10.0	4.44
5	Cylindrical	1.090	None	5.25

Table 2. Test Conditions for Diffuser Studies

$P_{t_{fe}}/\overline{P}_c$	$\overline{P}_c$, psia	P_{ti}, psia	T_{ti}, °F
2.34	3.28	7.85	100 to 110
2.02	3.28	6.85	100 to 110
1.62	3.28	5.50	100 to 110
1.48	3.28	4.98	100 to 110
2.20	6.30	14.13	100 to 110

NOMENCLATURE

D	Diameter, in.
L	Diffuser length, in.
P	Static pressure, psia
$\bar{P}_c$	Average of all test cell static pressure measurements, psia (see Fig. 7)
$P_{c_{sta}}$	Average test cell static pressure at a given station, psia (see Fig. 7)
P_t	Total pressure, psia
T_t	Total temperature, °F
X	Diffuser inlet plane location, in. (see Fig. 1)
x_c	Test cell station, in. (see Fig. 7)
Y	Centerbody position, in. (see Figs. 3 and 4)

SUBSCRIPTS

c	Test cell
d	Minimum diffuser duct diameter
ex	Exhaust
fe	Fan exit
i	Inlet
sp	Engine surface
sta	Test cell station